WHITEPAPER

Design & Development of High Efficiency Mechanical Drive Systems for Combine Platform

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March 2015

L&T Technology Services

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Abstract:

Today, agricultural equipment are getting smarter; customer preferences regarding farming practices, product type and features, vary by region. Manufactures are designing new combines on platforms that cover multiple classes to address these needs. Major subsystems in these new designs are mechanical belt drives. Belt drive systems are a key aggregate in combine harvesters, transmitting power to all sub-systems. The key benefit of belt drives is "Simple, Reliable (Machine Uptime) and cost effective power transmission drive system designs" which has become a unique selling point for combine harvesters. In this combine, the packaging of the drive system is quite challenging, since functional systems in the combines have been competitively sized to deliver higher throughput and grain quality. As a result the drives cannot be either oversized, which would exceed the weight/cost target or undersized, which would become unreliable. Hence optimized drives are necessary to deliver the required power.

L&T has developed and used NPD tools & techniques from its concept to development phase and also played a vital role in *DUTYCYCLE* definition which is critical to the proper sizing of the drive components. These new projects demand *concurrent engineering, complex design calculations & validation apart from robust implementation of project management tools and* techniques. L&T Technology Services' drive system design competency, can be used on various off-highway equipment to address each manufacturer's unique need for industry specific challenges.

1. Introduction

Belt drives are one of the cheapest & most efficient utility tools for power transmission between shafts that may not be axially aligned. Power transmission is achieved by specially designed belts and sheaves. The demand on a belt drive transmission system is large and this has led to many variations in design. They run smoothly with little noise, and cushion motor and bearings against load changes, albeit with less strength than gears or chains. However, improvements in belt engineering allow the use of belts in systems that only formerly allowed chains or gears.

Belt drives are simple, inexpensive, and do not require axially aligned shafts. It helps protect the machinery from overload and jam, while dampening and isolating noise and vibration. Load fluctuations are shock-absorbed (cushioned). They need no lubrication and require minimal maintenance. They have high efficiency high tolerance for misalignment, and are of relatively low cost if the shafts are far apart. Clutch action is possible by releasing belt tension. Different speeds can be obtained by stepped or tapered sheaves.

2. Importance of Optimal Belt Drive Design

- Suits compact environments
- Increases overall efficiency
- Reduces component size and weight
- Cost-effective
- Easy for assembling and servicing
- Standardizes and reduces the number of components
- Absorbs a good amount of shock and vibration
- Takes some degree of misalignment between the driven and the driver
- Enables long-distance power transmission, in comparison to other transmission systems

3. Process Flow

Process flow chart for the optimized belt drive design in shown in the Fig 1.

4. Duty Cycle and System Life

Duty cycle is a factor of how the machine is used in operating. It is defined as proportional to time during which a system is operated.

$$D = \left({}^{T}/_{P}\right) \times 100\%$$

Where D is the duty cycle, T is the time at level and P is the total period.

Duty cycle is the amount of power taken by the system in different operating conditions. Normally a current product as a percentage of time/cycle or lab test will be used to determine the exact duty cycle for a new system. This duty cycle will be used to re-size and select the components and to predict the lifespan of the system. Refer Fig 2.

Knowing that the duty cycle will result in a system designed in an optimized way, unavailability of proper data will lead to under or overdesign of the component which leads to premature failure of the system or a cost increase of the product.

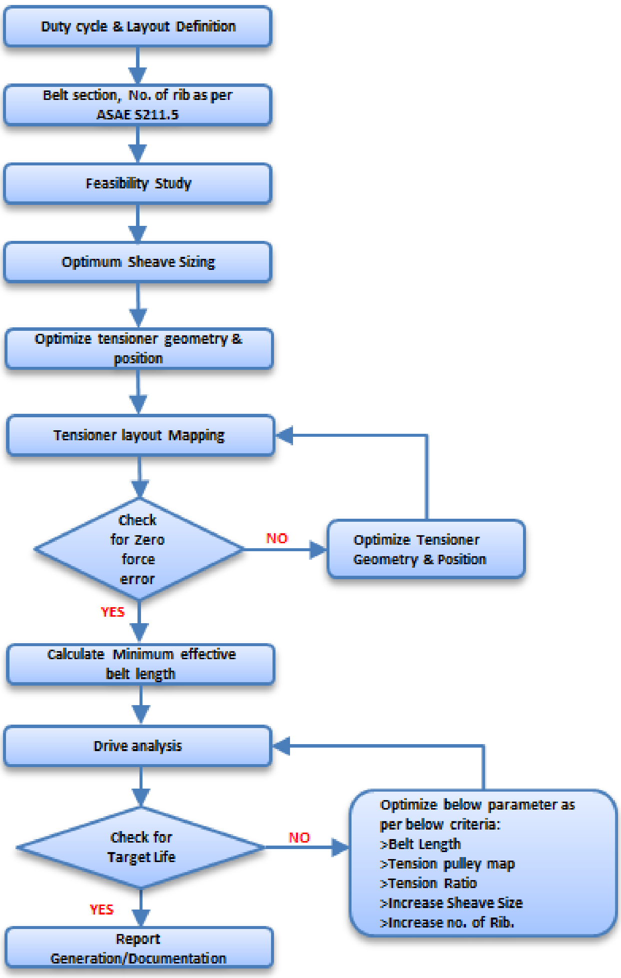
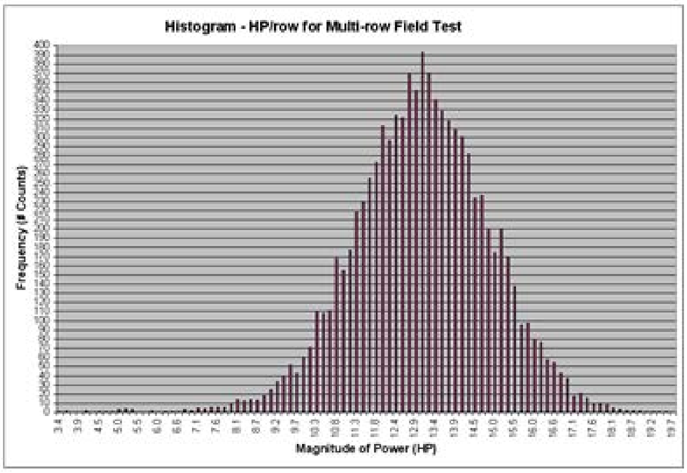


Fig 1. Process Flow

System life requirement is the manufacturer's target life span of the machine or subsystem using total system life requirement and duty cycle formation wherein each component's life can be insured to meet its target. So, an optimized product needs proper definition of the life of the product (refer Fig 3).



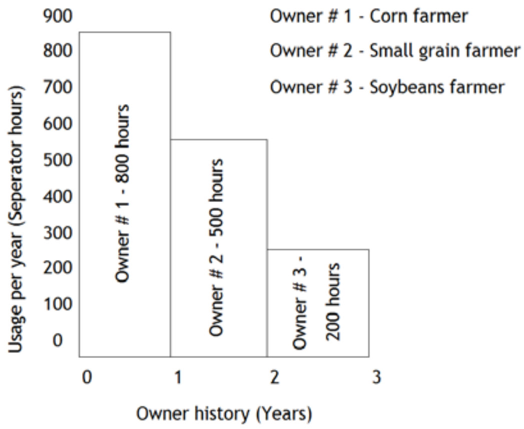


Fig 2. A Typical Duty cycle Representation

Fig 3. System Life

5. Belt Selection and Calculation

Table: 1. Belt properties

Polyester power transmission belts	Polyamide power transmission belts	Aramid Power transmission belts
The versatile belt	The hard-working belt	The sophisticated belt
Outstanding price-to-value ratio First choice of machine manufacturers and end users worldwide	Well known for its reliability and long service life Robust and highly resilient, copes with intermittent overload and high temperatures (up to 100 °C)	Best choice for long belts Short take-up and highest accuracy for numbers of revolutions (rpm) and belt speed
• Low energy consumption • Highly flexible • Simple to join • Reliable performance • Low energy consumption • Grooves enable high grip • Highly flexible • Simple to join	• Resilient • Shock resistant • Resilient • Shock resistant • Grooves enable high grip	• Low energy consumption • Highly flexible • Simple to join • High E-modulus

In order to guarantee problem-free running and to benefit from the features of a power transmission belt, the following three factors must be defined:

• Belt type
• Belt width
• Initial elongation

If one of these three factors change, the belt must be re-calculated. The professional specification of power transmission belts comprise the following steps:

1. Gathering the drive data
2. Selection of the optimal belt type

3. Calculation of the required belt dimensions

Nomenclature of a belt drive is shown in Fig 4.

d_L - Diameter of the larger sheave

d_S – Diameter of the smaller sheave

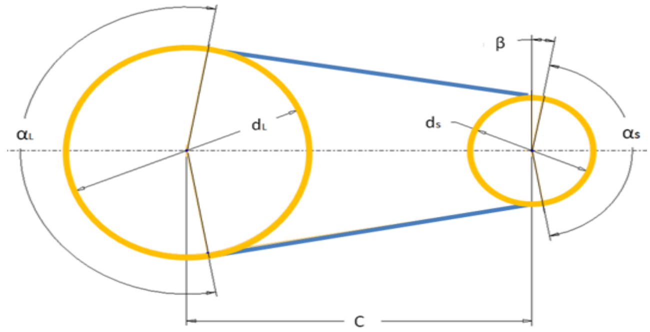
α_L - Angle of wrap of the larger sheave

α_S – Angle of wrap of the smaller sheave

C - Center distance between two sheave

$$\alpha_L = 180° + 2\beta$$

$$\alpha_S = 180° - 2\beta$$



Where angle β is,

$$\beta = \sin^{-1}\left(\frac{d_L - d_S}{2C}\right)$$

L_o = Length of open belt

$$L_o = \frac{\pi}{2}(d_L + d_S) + 2C + \frac{1}{4C}(d_L - d_S)^2$$

Fig 4. Belt Nomenclature

6. Velocity Ratio

Velocity ratio of belt drive is denoted as,

$$\frac{N_L}{N_S} = \frac{d_S + t}{d_L + t}(1 - s)$$

Where, NL and NS are the rotational speeds of the large and the small sheave respectively, s is the belt slip and t is the belt thickness.

7. Optimum Sheave Sizing

Sheave sizing is a major deciding factor on how a drive runs. Optimal sizing means to achieve desired velocity ratio and to size the sheave within the weight target without compromising the belt life.

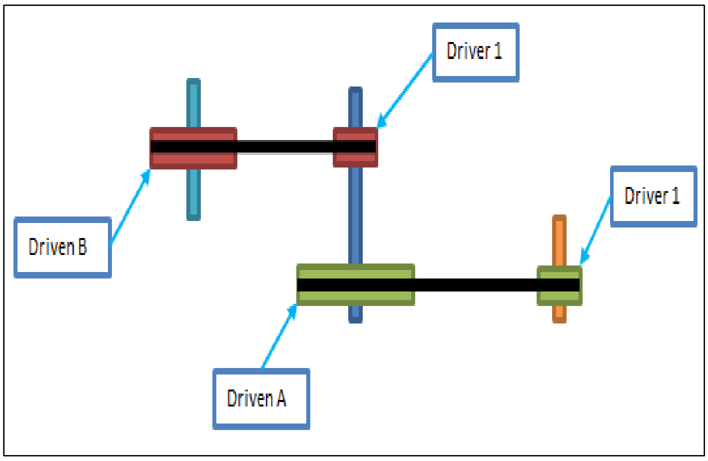


Fig 5. A Typical Drive System

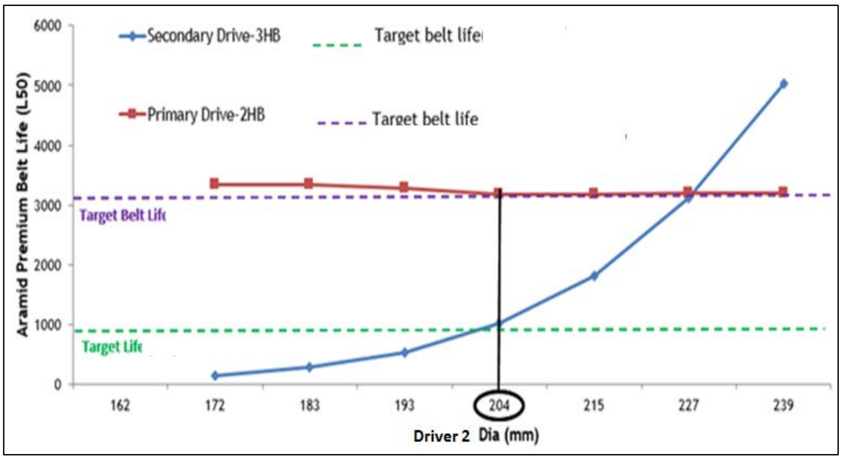


Fig 6. Sheave Sizing

Note: ASAE-S211.5 standards (V-Belt Drives for Agricultural Machines) to be referred for minimum sheave diameter selections.

Fig 5 shows a drive system where the power is transmitted from Driver 1 to Driven B through jackshaft. In this scenario, it is not accurate to arrive at sheave diameters by using the equations stated in belt calculation & velocity ratio. For instance, in the above mentioned case, power has to be transferred from Driver1 sheave to Driven B. The speed of these sheaves is implicitly implied by machines requirements. Diameters of sheave and jackshaft speed are the variables and thus, the logical relationship is derived.

The logical relationship of variables and the constants are programmed in a spreadsheet which shows the different possible combinations of sheave diameters against the velocity ratio. A excel based tool is used to create different possible combinations of sheave diameters which satisfy the velocity ratio and give graphical output (Fig 6.) representing optimum sheave diameter combination along with respective belt life.

8. Tensioner Layout Design & Zero Spring Force Error

V-belts operate on mechanical advantage of the wedging principle and friction principle. Appropriate tensioning of belt drive is supremely important to transmit the anticipated power. If sufficient tension is not produced, the drive will result in slippage, triggering rapid belt and sheave wear, and thus, reduce in productivity. If the belt tension is more, it can result in excessive stress on belts, bearings, and shafts and thus reducing efficiency and lifespan. Nevertheless, there is still a wide range of tension within which a drive will operate efficiently.

A tensioner is a spring loaded device that produces constant force on the slack side of belt. This tensioner insures that the intended power is being transmitted within the allowable limit of slip.

The key for power transmission is the tension ratio between tight side and slack side. It is based on rule of thumb 5:1 for sheave having belt wrap of 180°. If the actual wrap is greater than 180°, then the allowable tension ratio will be higher than 5:1 at on the other hand, if actual wrap is lesser than 180°, then the allowable tension ratio will be lesser than 5:1

Nomenclature of a tensioner layout is shown in Fig 7.

$$\text{Spring force: } \frac{SST \times b - SST \times a}{c}$$

Where,

SST – Slack side tension acting on belt

a & b – Distance between slack side tension and tensioner pivot point.

c - Distance between spring force and tensioner pivot point

Based on available design environment, tensioner layout has to be built in such a way that it will produce enough and constant slack side tension in belt with minimum angular displacement during belt wear.

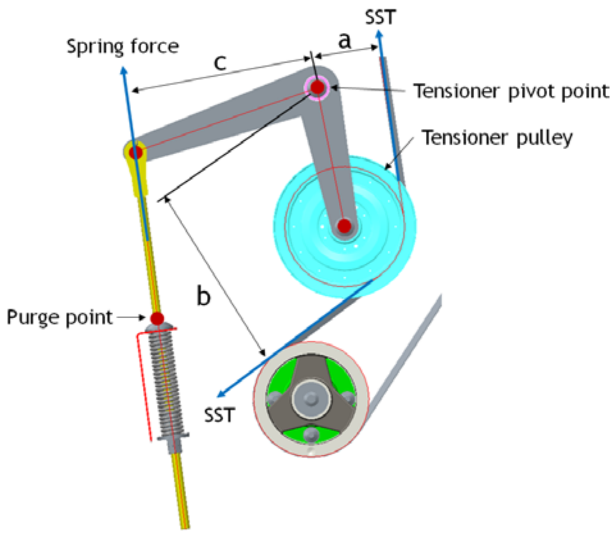


Fig 7. Tensioner Layout – Nomenclature

Table: 2. Optimum Tensioner Calculation

Tensioner position				
Tensioner position at LMC	deg	310		Refer snap-1
Tensioner position at NMC	deg	305.4		
Tensioner position at MMC	deg	300		
Tensioner position at MMC (1% Stretch)	deg	286		

Belt life matrix				
Part number				
		Aramid Std	Aramid Prem	
Belt life at LMC	L50	24750	25000	Life calculated using 5:1 tension ratio
Belt life at NMC	L50	25000	25000	
Belt life at MMC	L50	25000	25000	

Required spring force & Error			
Belt slack side tension at LMC	N	219.2	
Belt slack side tension at MMC (1% Stretch)	N	165.8	
No of rib		2	
A at LMC (New belt)	mm	60.4	Refer snap-2
B at LMC (New belt)	mm	270.6	
C at LMC (New belt)	mm	199.7	
D at LMC (New belt)	mm	209	
A at MMC(1 % Stretch)	mm	62.6	Refer snap-3
B at MMC(1 % Stretch)	mm	317.9	
C at MMC(1 % Stretch)	mm	183	
D at MMC(1 % Stretch)	mm	187.6	
Spring force required at LMC	N	461.5	
Spring force required at MMC (1% Stretch)	N	462.6	
Spring force error	N	-1	
Spring force error	%	0.25	

Spring			
Part number			
Spring free length	mm	279.4	
Spring rate	N/mm	8.4	
Max spring force	N	463	Considered max force of LMC & MMC (1%Stretch)
Gauge length	mm	224.3	

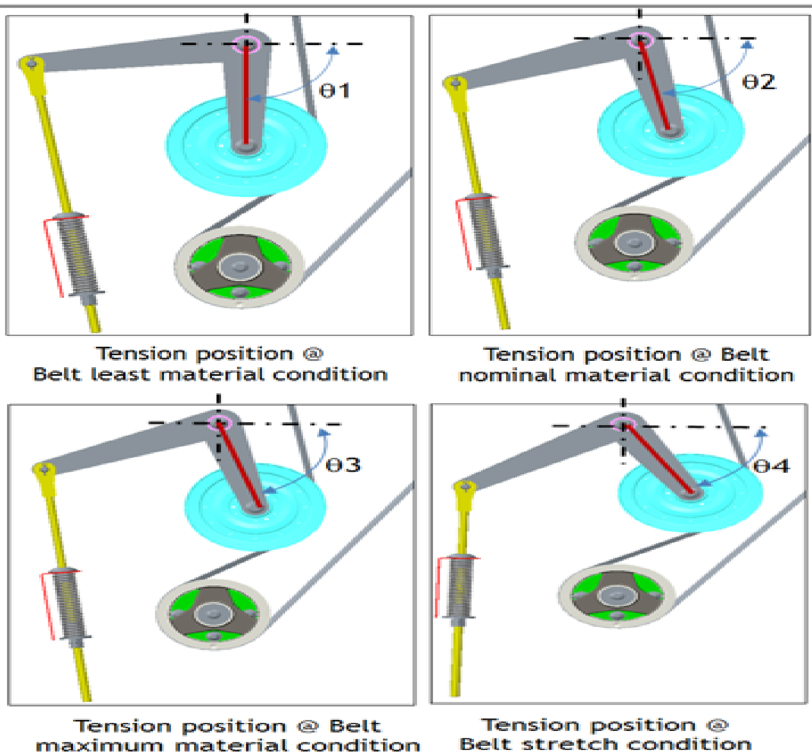


Fig 8.Tensioner Geometry Optimization

A mathematical model is created to form various tensioner layouts by changing a, b, c & SST values and come up with an optimum tensioner design, which can produce constant tensioner load for the entire belt life Table 2.

Zero force error: Irrespective of tensioner position (varies during belt wear as mentioned in below Fig 8.) the required spring force to produce belt slack side tension remains constant.

9. Installation Allowance

When designing a drive system for a manufactured product, allowance for belt installation must be built into the system. Installation allowance is basically determined based on the below formula

Belt Thickness x π/2 = Installation allowance

Any belt thickness which rides outside the sheave doesn't affect the ability to install the belt since we need enough additional length to slide over the outside diameter of the sheave. Minimum clearance between the adjacent belt spans is dependent on the amount of vibration in the spans.

During the belt installation process, it is very important that the belt be fully seated in the sheave grooves before applying final tension. Serpentine drives with multiple belts and drives with large sheaves are particularly vulnerable to belt tensioning problems resulting from the belt teeth being only partially engaged in the sheaves during installation. In order to prevent these problems, the belt installation tension should be evenly distributed to all belt spans by rotating the system by hand.

10. Belt Misalignment

In a belt drive, belt misalignment is one of the main reasons of belt failure. Depending on the extent of misalignment, belts can have a slow decrease in performance.

The degree of misalignment has a gradual reduction in the design life of the belt.

Allowable misalignment: To make the most of the performance and reliability of the belt drive, synchronous drives must be aligned carefully. This is not, though, a simple task in an assembly shop. For a belt drive, the extreme allowable misalignment, angular and parallel combined, is 1/4°.

It is not always easy to measure or quantify the angular misalignment. It is useful to take help of practical observations that appears on the belt to make a judgement of the relative misalignment.

Approaches to overcome misalignments:

- Hub with setscrews
- Tapered hub
- End-clamped hub
- End-clamped hub + OPV Machinery bushings

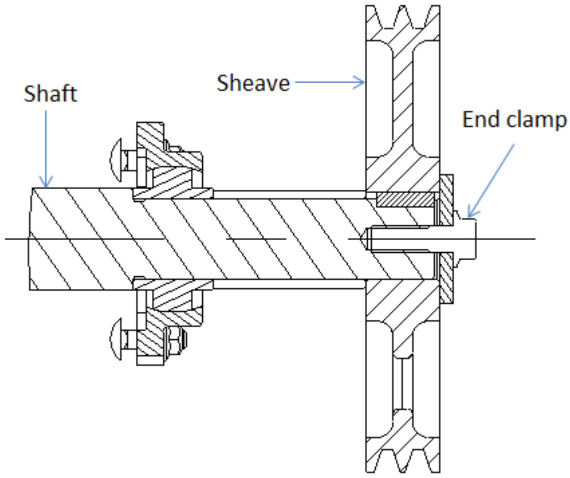


Fig 9. End clamping

Of all the approaches listed above, end clamped hub with OPV machinery bushing (Fig 9.) is suitable for agriculture machinery since it takes thrust load and allows to overcome misalignments. Method illustrated in Fig 9 is simple, robust and also increases shaft strength even though it requires a shoulder on the shaft.

11. Bolted Connection and Shear Bolt Design

Bolts are normally loaded in three ways 1.Tension, 2.Shear, 3.Combined shear and Tension. There are conditions where bending loads are applied on the bolt due to improper geometries of assembly.

Bolted connections are designed in such a way that it withstands tensile loading. Holes for bolts are made. Clearance holes and bolts with reduced shank diameter are commonly used. Joints in shear depend on the bolts to withstand the shear load and are not really strong. Importantly, relative sideward movement must take place before the bolt shank can take any shear load .It is also possible that in the case of components attached by a number of bolts that one bolt would be loaded first and this bolt would have to yield before the other bolts take their share of the shear load.

The most common over load protection method is using slip clutch or shear bolt connection. When the system is over loaded due to high material or plugging or any foreign objects obstructing the flow, more power is required by the system thereby damaging the internal components of the system.

Shear bolt is a mechanical fuse (safety device), sized to shear and disconnect the power transmission in the case of overload to prevent other parts in the drive system (Fig 10.)

Based on the maximum allowable torque in the system, the shear bolt can be designed. Joints should be loaded in shear so that the fasteners see no additional stress beyond the initial tightening.

Bolts can be in single shear or double shear based on the type of the design (Fig 11.). It is very important to ensure the design the threaded portion of the bolts not taking any shear.

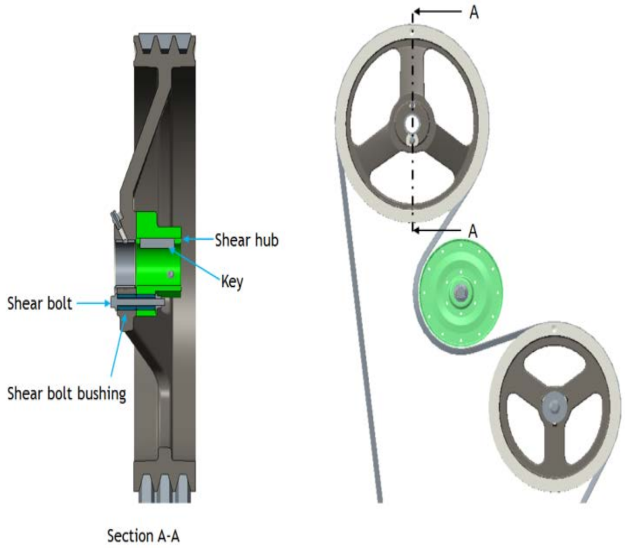


Fig 10. Shear Bolt Arrangement

Average shearing stress in the bolt:

$$fv = {}^{P}/_{A}$$

- P is the load acting on an individual bolt

- A is the area of the bolt and d is its diameter

Strength of the bolt:

$$P = fv \times \left(\frac{\pi d^2}{4}\right)$$

Where,

fv = shear yield stress = 0.6Fy

F – Force acting on plate

t – Plate thickness

d – Bolt diameter

C – Hole position from edge of plate

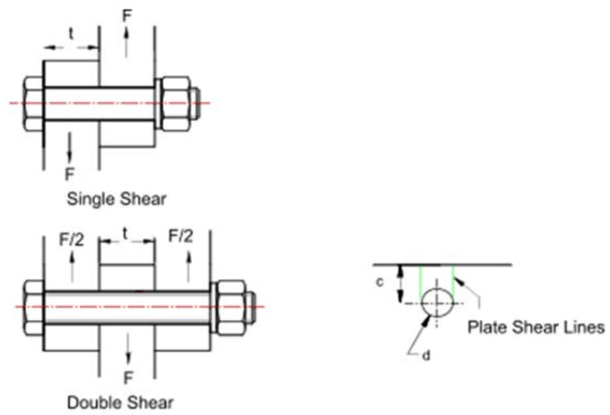


Fig 11. Shear Representation

12. Conclusion

An optimized design is the best and most cost effective design without “under” or “over” designing the drive. In many cases using engineering drive selection tables and manufacturers catalogues may work; it has certain limitations which is are known only to the person designing the drive. In any given application there are numerous possible combinations which give the required functional performance of the drive. Optimal performance requires evaluating all the variables.

Also the major causes of belt failures due to high and low belt installation tension. Other failures are due to environmental conditions like abrasive atmosphere, heat degradation, chemical degradation and foreign objects.

L&T has used NPD tools & techniques from the concept to the development phase and also played a vital role in DUTYCYCLE definition which is critical to size the drive components. Also, this project demands lot of concurrent engineering, design calculations & validation and project management tools and techniques. In the present scenario, to address the key challenges faced in the area of drive system designs by off highway industry, the developed competency on mechanical drives can be deployed to all L&T Technology Services existing/prospective customers by providing un-solicited proposals showcasing technical competency.

13. References

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